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Procedia Engineering 145 (2016) 1275 – 1282

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

Non-linear Finite Element Analysis of Offshore Stainless Steel Blast Wall under High Impulsive Pressure Loads

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Abstract

Typical blast walls of offshore platform are stainless steel light-weight walls installed to contain the effect of an accidental explosion on the topside of an offshore installation. These walls are mostly designed using simplified analytical techniques like single degree of freedom (SDOF) method using global deformation or displacement as primary response parameter. Thin plate structures like stainless steel blast walls when subjected to high impulsive pressure loads, may damage severely in a particular region without experiencing a significant global deformation. This study presents realistic responses of offshore blast walls under various high impulsive pressure loads generated from accidental hydrocarbon explosions by using detailed non-linear finite element analysis (NFEA). The numerical models were verified against past experimental study on similar metal blast panels. An extensive parametric study was conducted using the verified finite element models to construct pressure-impulse (P-I) diagrams for different deformation levels. These P-I curves or iso-damage lines can be used as a quick assessment tool to determine possible level of damage of similar offshore blast walls due to different high impulsive pressure loading caused from different explosion scenarios.

Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: Offshore blast wall; Impulsive loading; Non-linear finite element analysis; Pressure-impulse diagram.

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.164

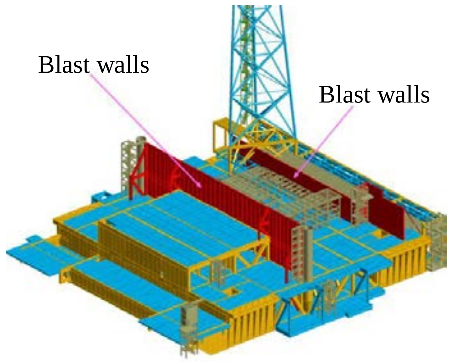
1. Introduction

The overgrowing energy demand is prompting the installation of offshore platforms in more remote and harsh environmental conditions where effective containment of possible accidental explosion is challenging. Although an explosion is a rare event in offshore installations, but a single explosion can be highly devastating. The risk of potential explosion rises during the drilling and conveying process of combustible crude oil in offshore platforms. Past incidents clearly demonstrate that hydrocarbon explosions can be extremely hazardous for offshore structures and can cause significant casualties, property loss and extreme marine pollution as was the case of Piper Alpha disaster in North Sea. Fig.1(a) provides a glimpse of the extent of devastation of Piper Alpha accident which resulted 167 casualties and $1.7 billion loss in term of properties and production [1].

To prevent structural damage to key installations and to protect personnel onboard, corrugated stainless steel panels (blast walls) are commonly used as a passive explosion proof on topside of offshore platforms. Popularity of stainless steel for blast wall material depends on its high ductility ratio, considerable energy absorption ability against impulsive loading and excellent corrosion resistance behavior. High yield and ultimate strength, long strain hardening behavior of stainless steel also make it as a preferred material for blast resisting design. Blast walls are normally installed to encircle the production module that deals with highly flammable oil and gas. A 3D model of an offshore platform with the locations of blast walls is shown in Fig.1(b). In the event of an explosion, blast containment structures are subjected to extreme high impulsive loading which involves large plastic deformation, high strain rate, weld tearing and localized permanent damage.

To improve the performance of blast walls a significant number of researches have been carried out since 1988 after Piper Alpha explosion. But most of the past studies and design guidelines are based on simplified analysis techniques. Often the blast wall design is based on elastic structural response using simplified blast pressure values, although the response of a blast wall is expected to be highly non-linear under realistic explosive loading. Simple analytical analysis technique based on single degree of freedom (SDOF) model is widely been used to find out dynamic responses of blast loaded structure. The available blast wall design guidelines, like Technical Note 5 (TN5) [2], unified facilities criteria manual (UFC 3-340-02) [3] and protective design center technical report [4] mostly prescribe the use of simplified analysis approach such as SDOF approach. Parameters used in SDOF models are converted from original continuous system to single spring-mass element, although it has proven to give reasonably accurate results for overall structural response but unable to indicate local damage of the structure. Moreover, those analyses are based on beam theory where blast walls are considered as a simply supported beam. Analysis results obtained from SDOF system without having realistic support conditions incorporated in the analysis will provide less reliable results.

(a)



(b)

Fig.1. (a) Piper Alpha Explosion [1]; (b) Topside of offshore platform with blast wall.

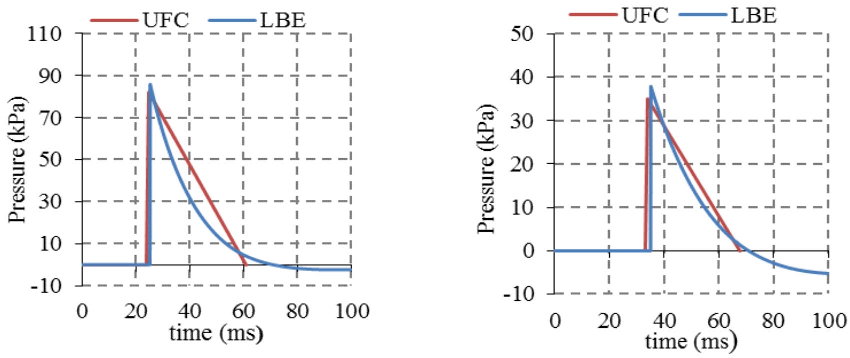
To overcome the limitations associated with simplified analytic methods, non-linear finite element analysis (NFEA) is often considered to the preferred approach for reliable structural response under high impulsive loading. Finite element (FE) analysis is more appropriate numerical analysis technique considering dynamic nature of blast loading, non-linear material properties and high strain effects in evaluating the structural response due to short duration high impulsive loading. Detailed study on the structural response of typical stainless steel protective walls and the effect of support rigidity of these walls has not been done before which can contribute significant overdesign of these walls for offshore structures. This current study focuses on investigating non-linear structural behaviour of corrugated stainless steel blast walls under impulsive pressure loading generated from different accidental explosions. Detail understanding of non-linear response of offshore blast walls and further improvement of design guidelines may significantly reduce the consequences of an accidental explosion on an offshore platform. The pressure-impulse diagrams presented in this research based on parametric study on non-linear FE models can be useful for quick assessment of potential damage level of a typical offshore blast wall under any given accidental explosion scenario.

2. Numerical modelling of blast wall

2.1 Finite element modelling and blast load application

In present investigation, numerical modeling was accomplished in commercial hydro-dynamic code LS-DYNA 971 [5], where the explicit numerical algorithm has widely been recognized for non-linear blast and impact simulation. To achieve the reliability and accuracy of the numerical modeling, analysis results and modeling techniques were verified against experimental results. Shell element Belytschko-Tsay from LS-DYNA material library was used for modeling the blast wall as this element has widely been used and was found to provide reasonably good results for analyzing blast impact on thin structure, non-linear analysis of large deformation and material non-linear response of impulsive loading [6]. Final mesh size was selected after preforming mesh sensitivity analysis. During mesh sensitivity analysis, it was observed that inadequate meshing produce premature failure in bending due to extreme overpressure. Plasticity and strain rates were also highly sensitive to the element seizing. Mesh sensitivity analysis results indicated a total number of elements around 15000 can provide an acceptable level of accuracy without increasing the computational resource requirement significantly.

In this research, simulation of high impulsive pressure loads generated from possible explosion was performed using empirical blast loading functions of prescribe in conventional weapon effect calculation tool CONWEP [7]. These loading functions are widely used and accepted for idealizing the pressure curves generated from a typical explosion. LS-DYNA keyword LOAD_BLAST_ENHANCED provides an engineering (empirical) model of air blast, in addition to free air blast, identical to the CONWEP functionality. This load simulation was implemented exactly following charts provided in UFC 3-340-02 [3]. This pressure function is well calibrated empirical equation based on numerous experimental results. Load pressure profiles for finite element simulation were established using both UFC chart and LOAD_BLAST_ENHANCED (LBE) and are presented in Fig. 2.



(a) (b)

Fig. 2. Pressure profiles from UFC and LBE (a) 5000 kg TNT (Z=2.92) (b) 1400 kg TNT (Z=4.46)

2.2 Material modeling and strain-rate effect

Incorporation of appropriate material non-linearities is important for performing reliable dynamic analysis as material non-linearity has a considerable effect on structural responses and failure modes of structural elements under impulsive load. To model stainless steel structural elements in FE method, simplified elasto-plastic, elastic perfectly plastic and rigid plastic stress-strain relationships are often used. Due to prolonged and near-linear strain hardening behavior of stainless steel, those simplified material models can provide reasonably good idealization of the actual material behavior. For FE modeling material properties of stainless steel (316L) were defined with isotropic strain hardening (Material Type 3 in LS-DYNA) with density ρ = 7850 kg/m^3, Young's modulus E = 200,000 MPa, Poisson's ratio ϑ = 0.3, yield stress σ_0.2 = 316 MPa and a tangential hardening E_t = 1.25 GPa. Geometric dimensions and material properties for the FE models were taken from HSC research report 124 [8] as the experimental results presented in that study were used to verify the developed FE models. The selected material model for stainless steel is suited to model isotropic and kinematic hardening plasticity with the option of including strain rate effects and this material model is found to be cost effective and available for shell, solid and beam type elements [9].

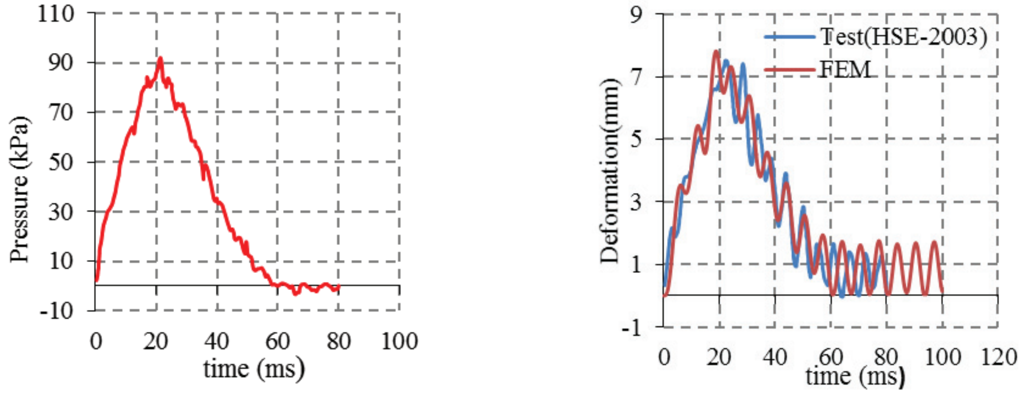
The range of strain rates involved in the structural response of a structure under short duration high magnitude impulsive loading is significantly high compared to the ranges associated with other common dynamic loads like earthquake. Stainless steel (316L), used for modelling the blast walls, is a strain rate sensitive material particularly at the region of 0.2% proof stress. There are several approaches that can be adopted to incorporate the effect of strain rates in the analysis or design of blast resistant structures. One of the most commonly employed constitutive equations adopted in numerical modeling for steel and similar materials for high strain rates is the application of Cowper–Symonds equation [10]. Cowper-Symonds equation mentioned in Eq (1) has already been adopted by most of the finite element based software.

$$\frac{\sigma}{\sigma_s} = 1 + \left(\frac{\varepsilon}{D}\right)^{\frac{1}{q}} \tag{1}$$

where σ and σ_s are the dynamic and static yield stress, respectively, ε is the strain rate and, D and q are the curve-fitting material constants. In order to consider strain rate effect, main parameters of its equation D and q are 40.5 and 5 respectively for stainless steel (316L).

2.3 Validation of finite element models

Finite element model was established based on the geometric and material properties of ¼-scale test panel [8] and the support conditions were simulated as closely as possible to the experimental set-up. Simulated results were compared with the experimental results to verify the modeling techniques, boundary conditions and application of highly impulsive pressure loads. The pressure time history applied to the finite element model is shown in Fig. 4(a). The deformation time histories obtained from finite element analysis and from the test are shown in Fig. 4(b). The deformation history obtained from the simulated finite element model shows that the geometric model, selected material models and applied support conditions could produce response similar to the actual response observed during the test.

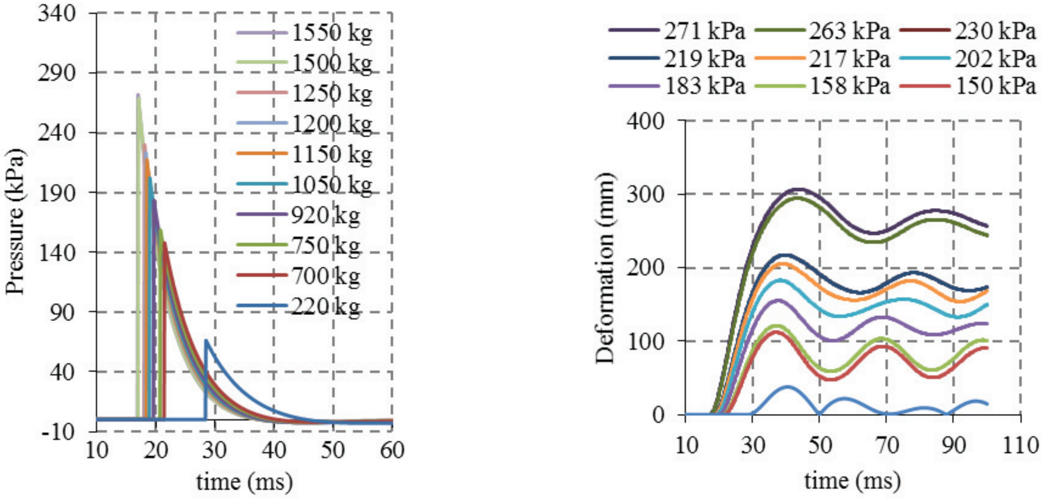


(a) (b)

Fig. 3. (a) Pressure time history of 90 kPa; (b) Comparison between test and FEM

3. Structural response of blast walls

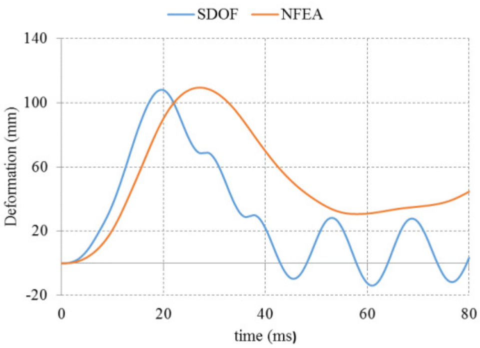
Responses of the modelled blast wall were obtained for different high impulsive loading conditions. Various pressure profiles were used to simulate different possible explosion scenarios by changing the weight of explosive charges that generates the pressure curves. Fig. 5.(a) shows different blast pressure history from a 20 m stand-off distance where explosive charge weights are also mentioned, resulted deformation history are shown in Fig. 5. (b).

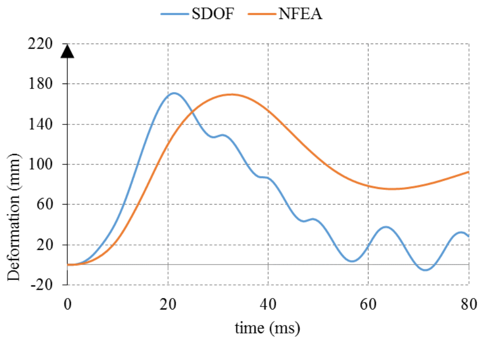


(a) (b)

Fig. 4. (a) Applied pressure profiles; (b) resulted deformation time histories

Past studies have established that typical blast pressures an offshore blast wall is expected to experience in the event of an explosion is in the range between 170 kPa to 370 kPa [11]. Therefore, initially explosive weights were chosen to get blast pressure in that range and later it was varied in wider range of pressures and impulses to explore the structural behavior under extreme and less common explosion events. Hydrocarbon blast pressure profiles can vary widely and the deformation patterns of blast walls are distinctive for each type of pressure loading. It is obvious from the FE simulation results that structural response of a blast wall largely depends on loading rate, boundary conditions and material properties. Blast walls analyzed by NFEA, were also analyzed using SDOF approach. Widely used equivalent SDOF method was used for the SDOF analysis. One full panel of a blast wall was modeled in SDOF analysis, equivalency factors proposed by Biggs [12] were used to convert the actual structure to equivalent SDOF model. Details on SDOF analysis of blast walls can be found in Rahman at el. (2015)[13]. Fig. 5 shows the deformation response obtained from both SDOF model and NFEA. Although, the peak deformation values for both the analytical approaches are similar, but peak response times are different. Moreover, the SDOF only provides the peak deformation of pre-defined critical point, whereas the NFEA provides the detailed response and damage distribution for a steel wall under impulsive loading.



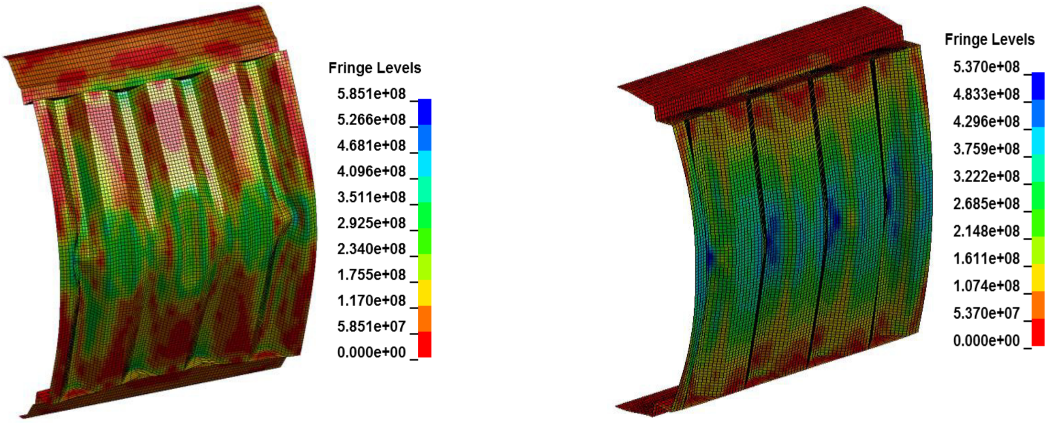


(a) (b)

Fig. 5. Deformation histories obtained using SDOF analysis and NFEA: (a) for 133 kPa peak pressure; (b) for 160 kPa peak pressure

4. Results and discussion

Analysis results were studied extensively focusing on specific response parameters like deformation, maximum stress, and maximum strain were formed for different pressure profile. Deformation is a critical parameter for representing structural response and widely been used in various design guidelines as allowable deformation limits. For each loading condition, various response parameters were recorded and compared with other loading conditions. Von-Mises stress contours obtained for the same blast wall under different high impulsive loadings with different peak pressure values are shown in Fig. 6. The figure clearly shows significantly different damage patters for blast wall under different loading conditions and the response patterns cannot be properly captured by SDOF analysis.



(a) (b)

Fig. 6.Von-Mises stresses (a) for 256 kPa pressure, 3.86 kPa-s impulse; (b) for 107 kPa pressure, 1.51kPa-s impulse.

Trinitrotoluene (TNT) equivalence method is commonly used to characterise various types of explosions in protective analysis and design. In this approach blast pressure profiles are obtained from a combination of stand-off distance and equivalent weight of TNT-charge. Table 1 shows some selected results from the parametric study to demonstrate the relation between the applied load and impulse and resulting deformations and stresses developed in the stainless steel blast wall.

Table 1: Results from parametric study

Charge weight, TNT (kg)	Scale distance, Z (m/kg)	Peak Pressure, P_{peak} (kPa)	Impulse, I (kPa-s)	Maximum deformation, U (mm)	Maximum stress, σ_{Max} (MPa)	Maximum Strain, ε_{Max}	Energy, E (kJ)
550	2.25	233	1.724	160	520	0.146	266
600	2.20	247	1.852	176	534	0.161	303
650	2.14	263	1.998	195	549	0.162	343
680	2.12	274	2.137	207	551	0.162	367
700	2.10	280	2.226	214	552	0.167	384
850	1.98	325	2.795	281	557	0.174	517
920	1.93	348	2.923	311	561	0.266	584
1500	2.62	107	1.509	103	395	0.034	148
2500	2.21	155	2.286	200	541	0.147	348

The results in Table 1 demonstrate that the maximum deflection of a blast wall depend on the combination of peak pressure and amount of impulse. As both the peak pressure and impulse are important to relate structural response to loading parameters, often pressure-impulse (P-I) diagrams are used to relate the level of structural response and damage to the loading parameters. P-I diagrams for the modelled blast wall based on five separate deformation levels were established by repeated NFEA. Each of analysis generates a certain value of pressure and impulse which represents a single point in the graph. All of those points are in a part of separate group while groups are belonged to each deformation level. Fig. 7 shows deformation based pressure-impulse diagram where all the responses are categorized in five separate levels of deformation.

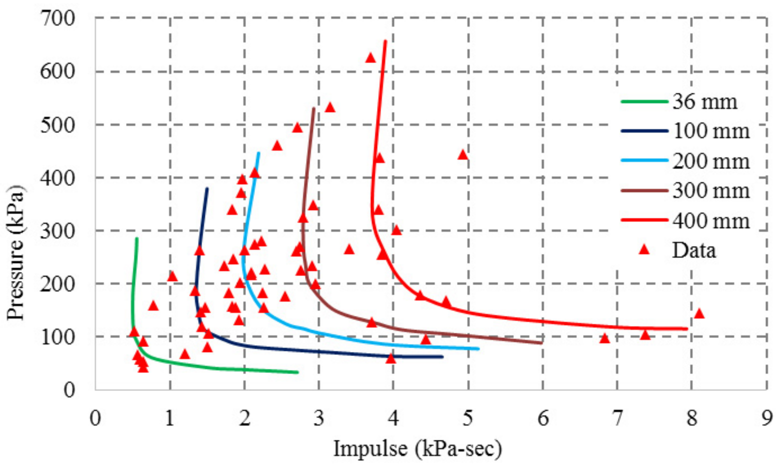


Fig. 7. Pressure–Impulse diagram for various deflection levels for different pressure profiles

P-I diagrams in Fig. 7 can be used as a rapid blast response assessment tool without performing any extensive NFEA analysis. Each deformation level has its own particular range from lower limit to upper limit. Two primary input data from explosion as peak pressure and impulse are required to evaluate level of response for any explosion. After plotting pressure vs. impulse, each analysis gave one point in the curve. By evaluating the position of the point the level of deformation can be easily identified.

5. Conclusion

The aim of this study was to present the structural response of offshore blast walls under high impulsive loadings generated from accidental explosions. Realistic simulation and idealization of hydrocarbon blast by using available technical guidelines were employed. Detailed structural responses of offshore blast walls under various levels of impulsive loadings are presented. Comparison between SDOF model and NFEA is also presented to demonstrate that even though SDOF models can predict reasonably accurate results but for blast walls damage distribution is not often confined to the mid span only. Pressure-impulse diagrams were developed to relate the blast load parameters with the response of a blast wall. These P-I diagrams can be used as a rapid blast response assessment tool without performing any extensive NFEA analysis for typical stainless steel blast walls used in offshore platforms. Finally, the developed P-I curves can be helpful for designing or damage assessment of offshore blast walls under different explosions.

Acknowledgement

The authors gratefully acknowledge the financial support of the Center on Sustainable Built Environment and Office of Research at Abu Dhabi University.

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